2014 IEEE International
Symposium on Antennas and Propagation and
USNC/URSI National Radio Science Meeting

A Technique for Designing Flat Lenses Using Artificially Engineered Materials

Ravi Kumar Arya, Shaileshachandra Pandey and Raj Mittra
EMC Lab, The Pennsylvania State University

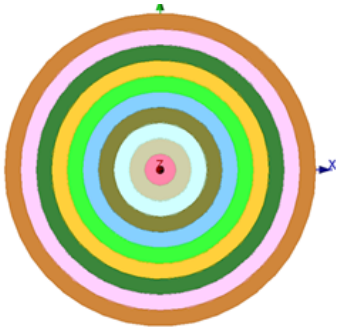
PENNSTATE
1855

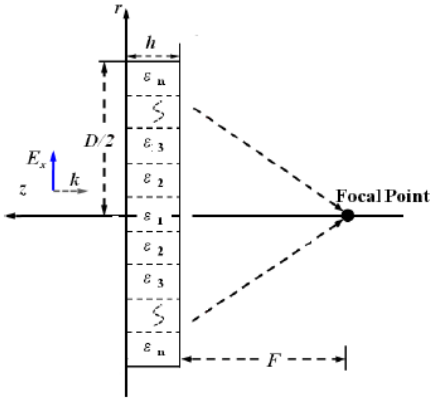
July 6-11, 2014 • Memphis, Tennessee USA

Different Lens Designs

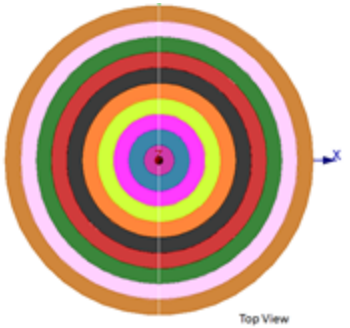
(F/D=0.25 at design center frequency f_c=30GHz)

1. RO Lens



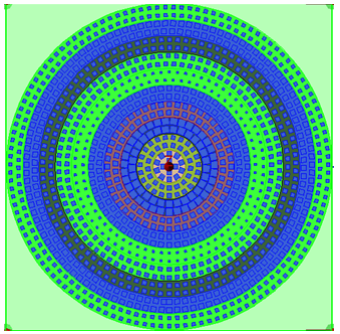


2. RO (ZP) Lens



3. RO (ZP) COTS* lens

4. RO/RO(ZP) lens with artificially engineered dielectrics / Dial-a-dielectric (DaD)



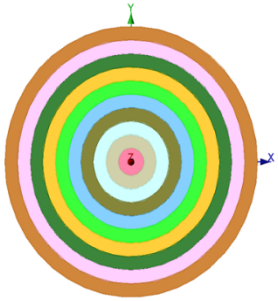
5. TO# lens

RO: Ray Optics
ZP: Zone-plate
*COTS: Commercial Off-the-shelf (Rogers Corporation)
TO: Transformation Optics

Different Lens Designs

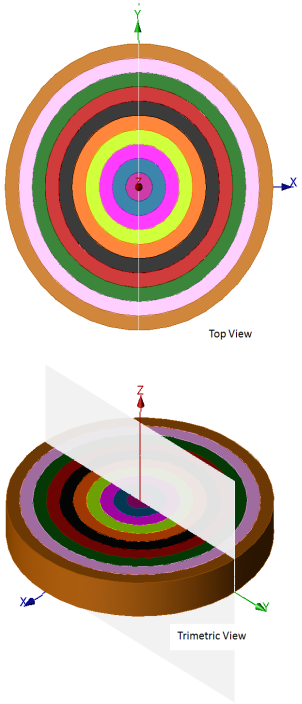
RO lens

RO: Ray Optics



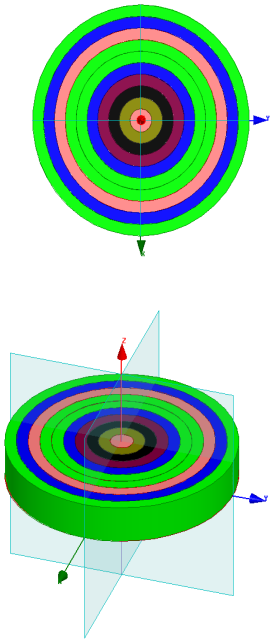
RO (ZP) lens

ZP: Zone-plate



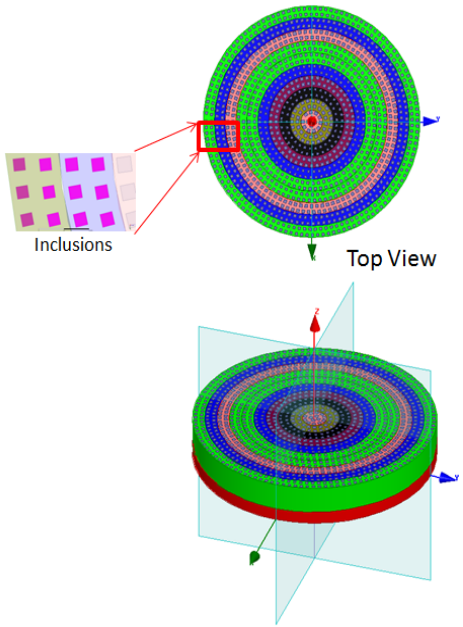
RO (ZP) COTS* lens

*COTS: Commercial Off-the-shelf



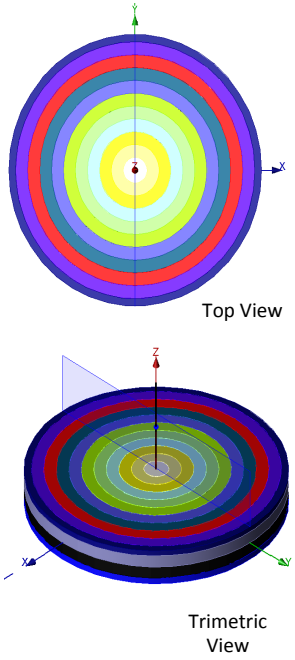
DaD

(Dial-a-dielectric)



TO # lens

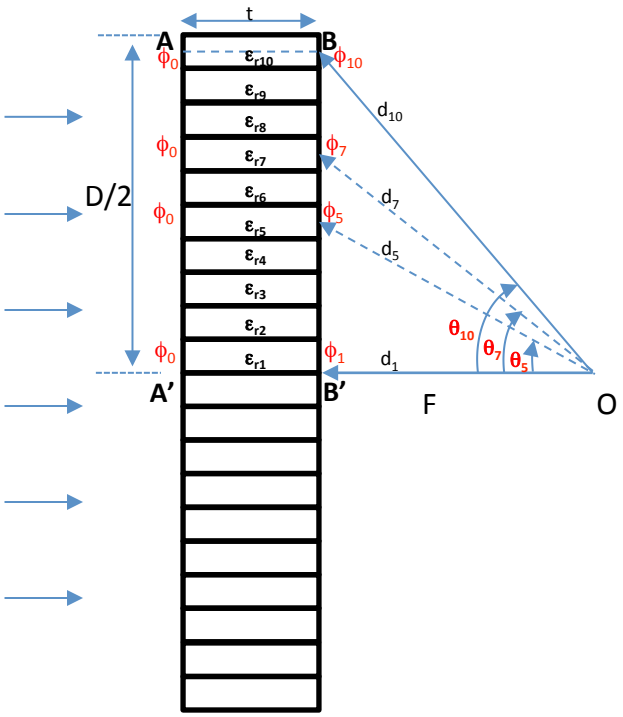
TO: Transformation Optics



Directly calculated, dielectrics are not commercially available. Next slide shows the design approach	**Some rings of RO Lens are zoned to bring dielectric constants down. Lower dielectrics are more easily available.**	**Designed using nearest available COTS materials**	**New improved design using available COTS materials**	**Often leads to designs based on metamaterials that can be difficult to realize**

RO Lens Design

Calculation of path length for RO Lens



Phase at right side of lens for ring N = ϕ_N (N varies from 1 to 10) assuming ϕ_0 =0

For finding optical path length following parameters are specified:

i) Focal length(F) : 15.875mm

ii) Diameter (D) : 63.5mm

iii) Thickness(t) : 9mm

iv) Frequency(f_c): 30GHz

For achieving equality and constructive interference at focal point of lens, the materials were chosen for optimum design.

AB+BO=A'B'+B'O

$$\phi_{10} + k_0 d_{10} = \phi_1 + k_0 d_1$$

$$\phi_1 + k_0 d_1$$

$$= (2\phi/\phi)*9\text{mm}* \sqrt{11.15} + (2\phi/\phi)*15.875\text{mm}$$

= 28.85

$$\phi_{10} + k_0 d_{10} \quad (\phi_{10} = k_{10} * t * \sqrt{\phi_{r10}})$$

$$= (2\phi/\phi)*9\text{mm}* \sqrt{1.73} + (2\phi/\phi)*34.085\text{mm}$$

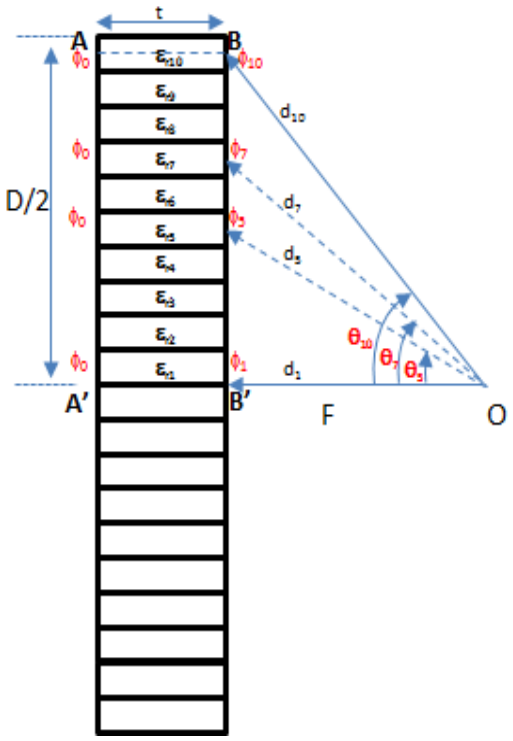
= 28.85

S. Jain, M. Abdel-Mageed and R. Mittra, "Flat-Lens Design Using Field Transformation and Its Comparison With Those Based on Transformation Optics and Ray Optics," Antennas and Wireless Propagation Letters, IEEE , vol. 12, pp. 777–780, 2013

RO Lens Design

Calculated dielectric values

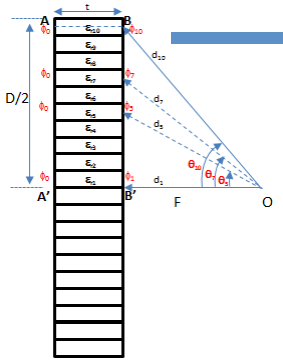
Calculated Dielectric properties of different ring materials are shown in table for constructive interference at focal point.



Ring No.	Dielectric Material ε_r	Path lengths F/D=0.25
1	11.15	28.85
2	10.64	28.85
3	9.8	28.85
4	8.7	28.85
5	7.45	28.85
6	6.15	28.85
7	4.88	28.85
8	3.7	28.85
9	2.64	28.86
10	1.73	28.85

S. Jain, M. Abdel-Mageed and R. Mittra, "Flat-Lens Design Using Field Transformation and Its Comparison With Those Based on Transformation Optics and Ray Optics," Antennas and Wireless Propagation Letters, IEEE , vol. 12, pp. 777–780, 2013

Material parameters for F/D=0.25 @ f_c = 30GHz



RO lens

Directly calculated, dielectrics are not commercially available

Ring No.	1	2	3	4	5	6	7	8	9	10
$\varepsilon_{desired}$	11.15 Usually at High value, no COTS	10.64	9.8	8.7	7.45	6.15	4.88	3.7	2.64	1.73

RO (ZP) lens

Zoning on rings 1-7, results in different $\varepsilon_{desired}$

Ring No.	1	2	3	4	5	6	7	8	9	10
$\varepsilon_{desired}$	4.96	4.62	4.08	3.38	2.62	1.87	1.20	3.7	2.64	1.73

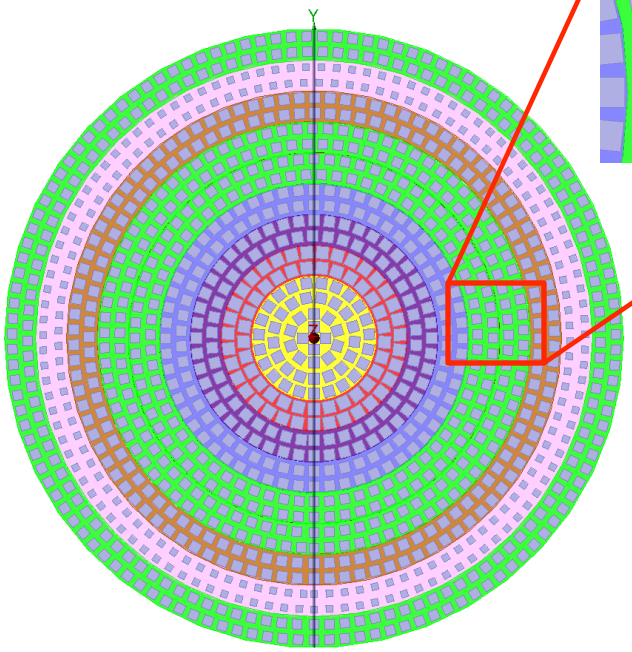
RO (ZP) COTS lens

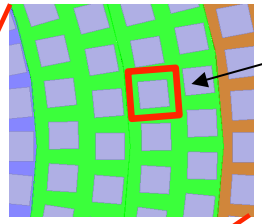
Using nearest COTS material for above lens

Ring No.	1	2	3	4	5	6	7	8	9	10
Epsilon	4.7	4.5	3.66	3.27	2.5	1	1	3.66	2.5	1

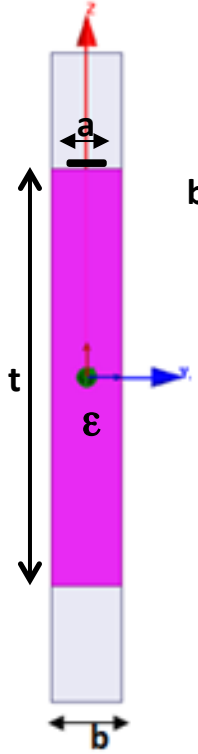
DaD Strategy-1: Obtaining higher dielectric than base material
Design of artificial material using single dielectric

Printing the square patch on top of the unit cell (i.e. dielectric medium) to realize the magnitude and phase which corresponds to desired ε_r

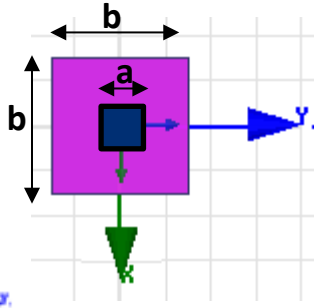




Unit Cell



Side View

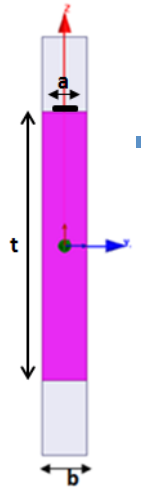


Top View

Lens is comprised of multiple rings and each ring is discretized into multiple unit cells.

b=1.58mm, t=9mm

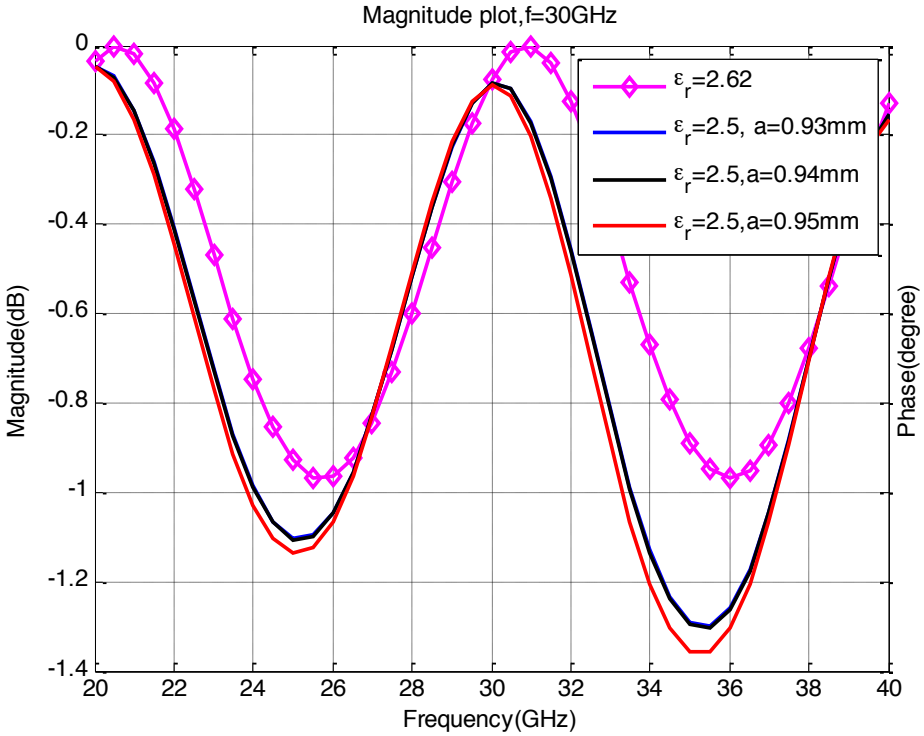
DaD Example-1 : Obtaining material of $\varepsilon_{desired} = 2.62$ using $\varepsilon_r = 2.5$ and patch

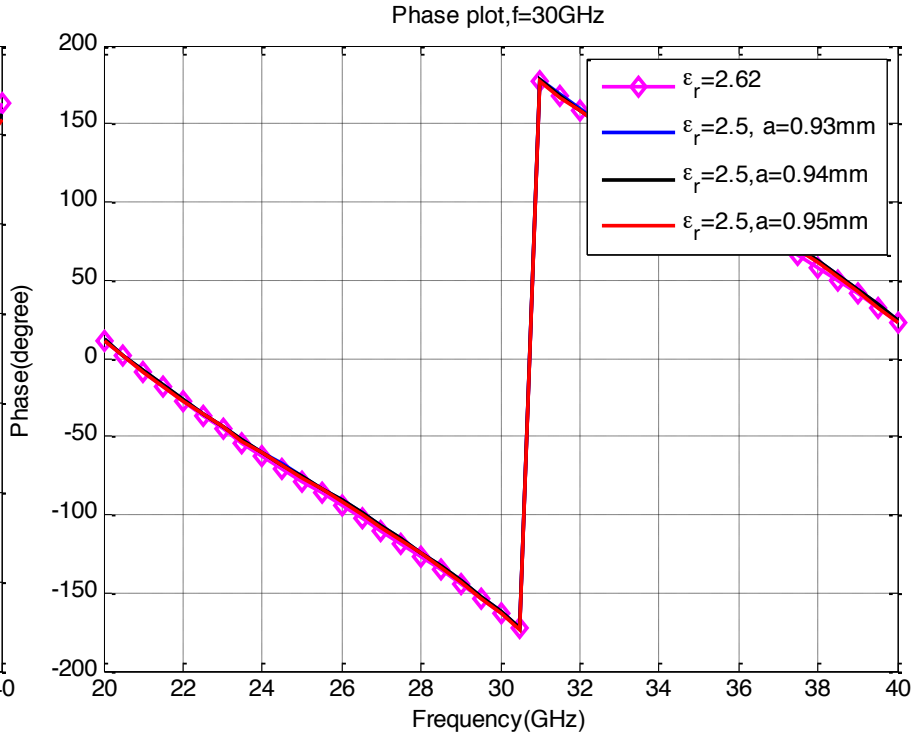


b=1.58mm, t=9mm

We change the unit cell patch dimensions so that it gives phase difference (S_{21} Phase) equal to given by unit cell of $\varepsilon_{desired}$, keeping acceptable S_{21} magnitude .

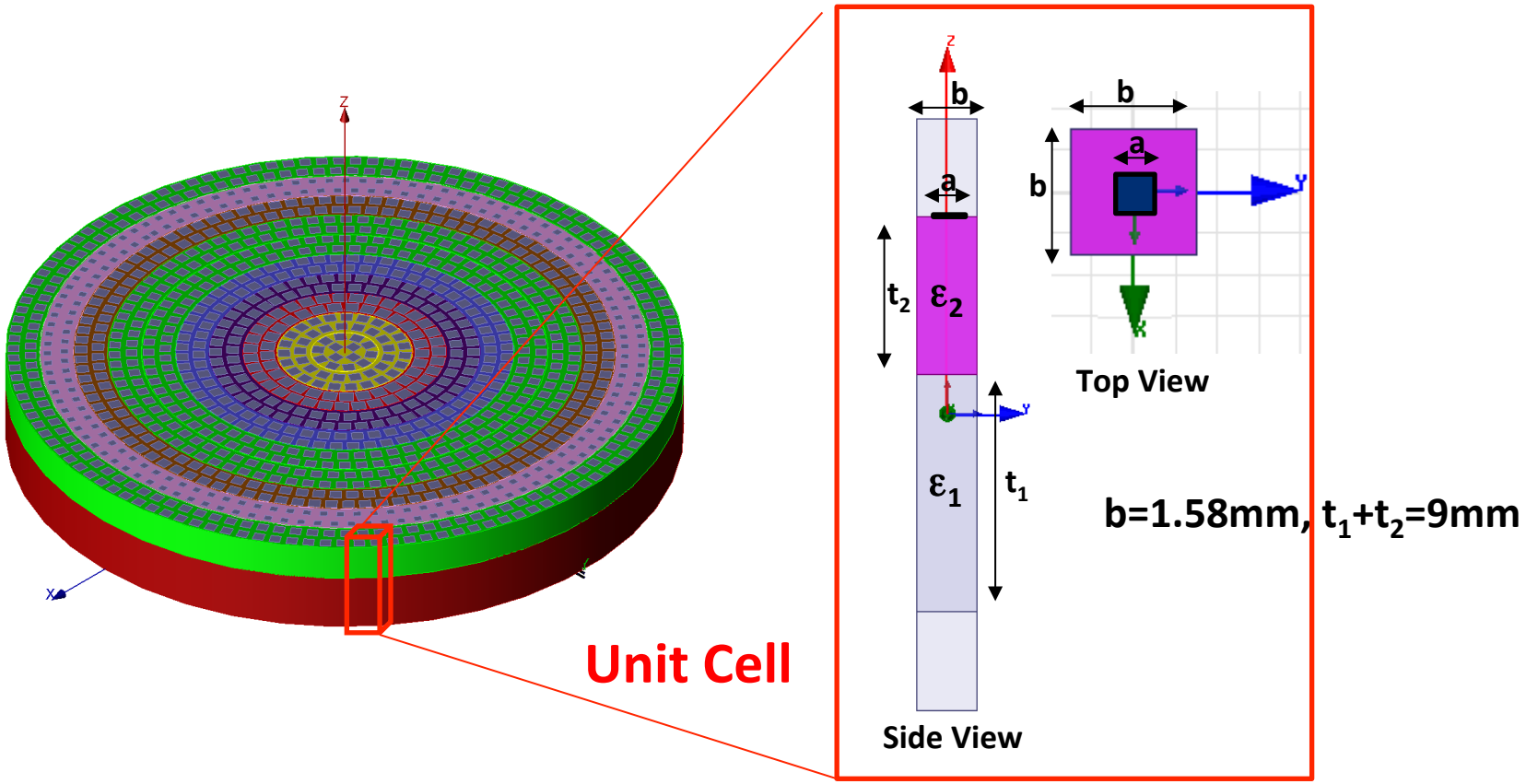
f = 30GHz	$\varepsilon_{desired} = 2.62$	a=0.93mm	a=0.94mm	a=0.95mm
Mag.(dB)	-0.07	-0.082	-0.082	-0.087
Phase.(Deg.)	-163	-162	-162	-163



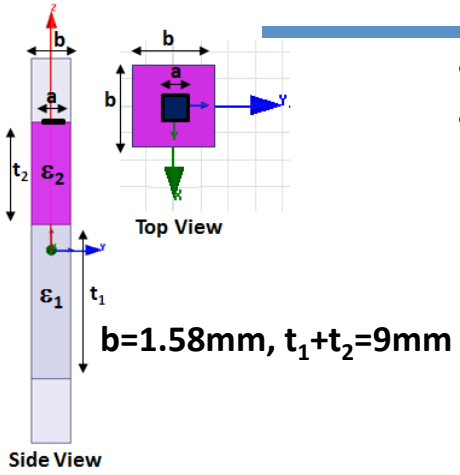


DaD Strategy-2: Obtaining lower dielectric than base material
Design of artificial material using multiple dielectrics

- Vary the thickness of unit cell (i.e. dielectric medium)
- Print the square patch on top of the unit cell to realize the magnitude and phase for $\varepsilon_{desired}$



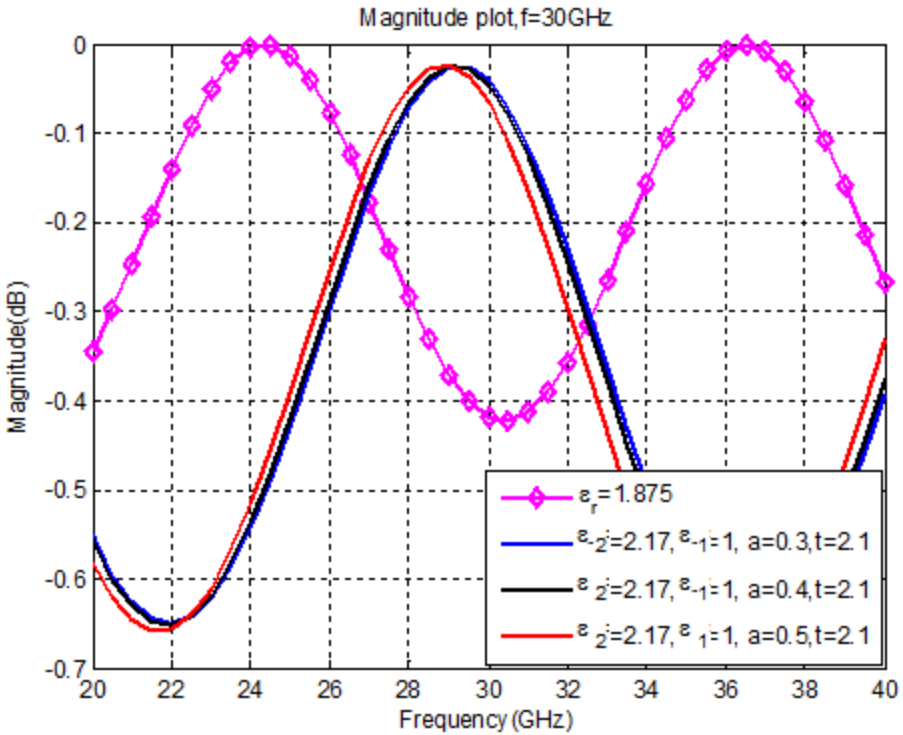
DaD Example-2 : Obtaining material of $\varepsilon_{desired}$ = 1.87 using ε_2=2.17, ε_1=1.0 and patch

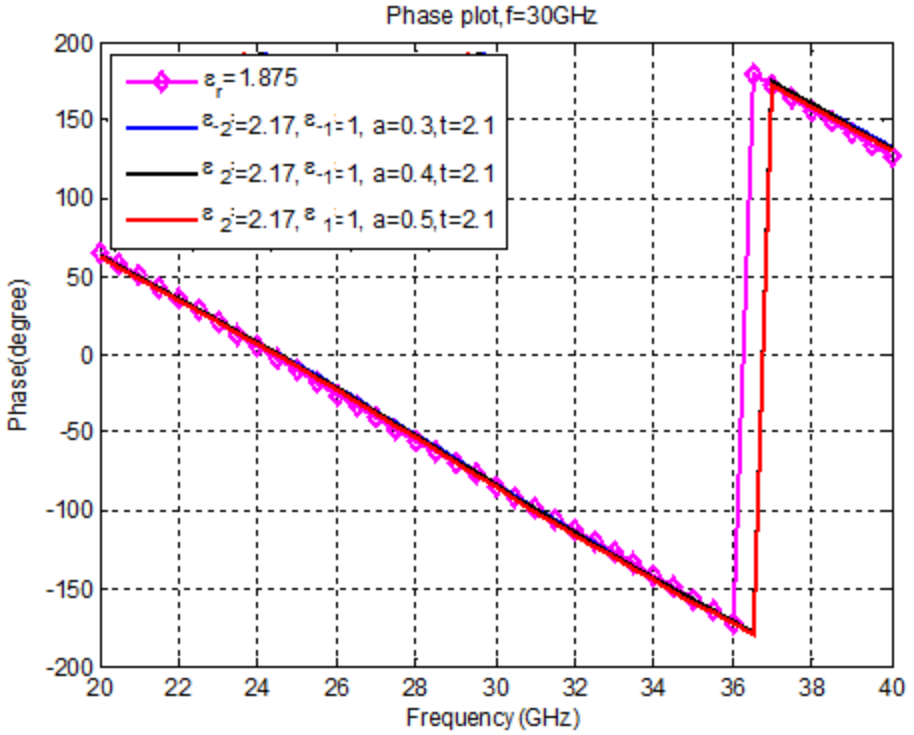


b=1.58mm, t_1+t_2=9mm

- First, change t_1/t_2.
- Then, we change the unit cell patch dimensions so that it gives phase difference (S_{21} Phase) equal to given by unit cell of $\varepsilon_{desired}$, keeping acceptable S_{21} magnitude .

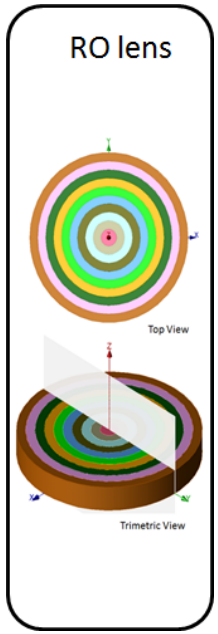
f = 30GHz	$\varepsilon_{desired}$ =1.87	ε_2=2.17, ε_1=1.0, t_1=2.1mm, a=0.3mm,	ε_2=2.17,ε_1=1.0, t_1=2.1mm, a=0.4mm,	ε_2=2.17,ε_1=1.0, t_1=2.1mm, a=0.5mm,
Mag.(dB)	-0.417	-0.040	-0.040	-0.065
Phase (Deg.)	-84	-83	-84	-85

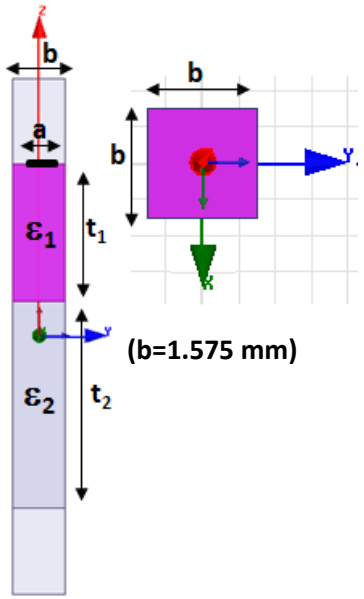




RO lens

(Different configurations)

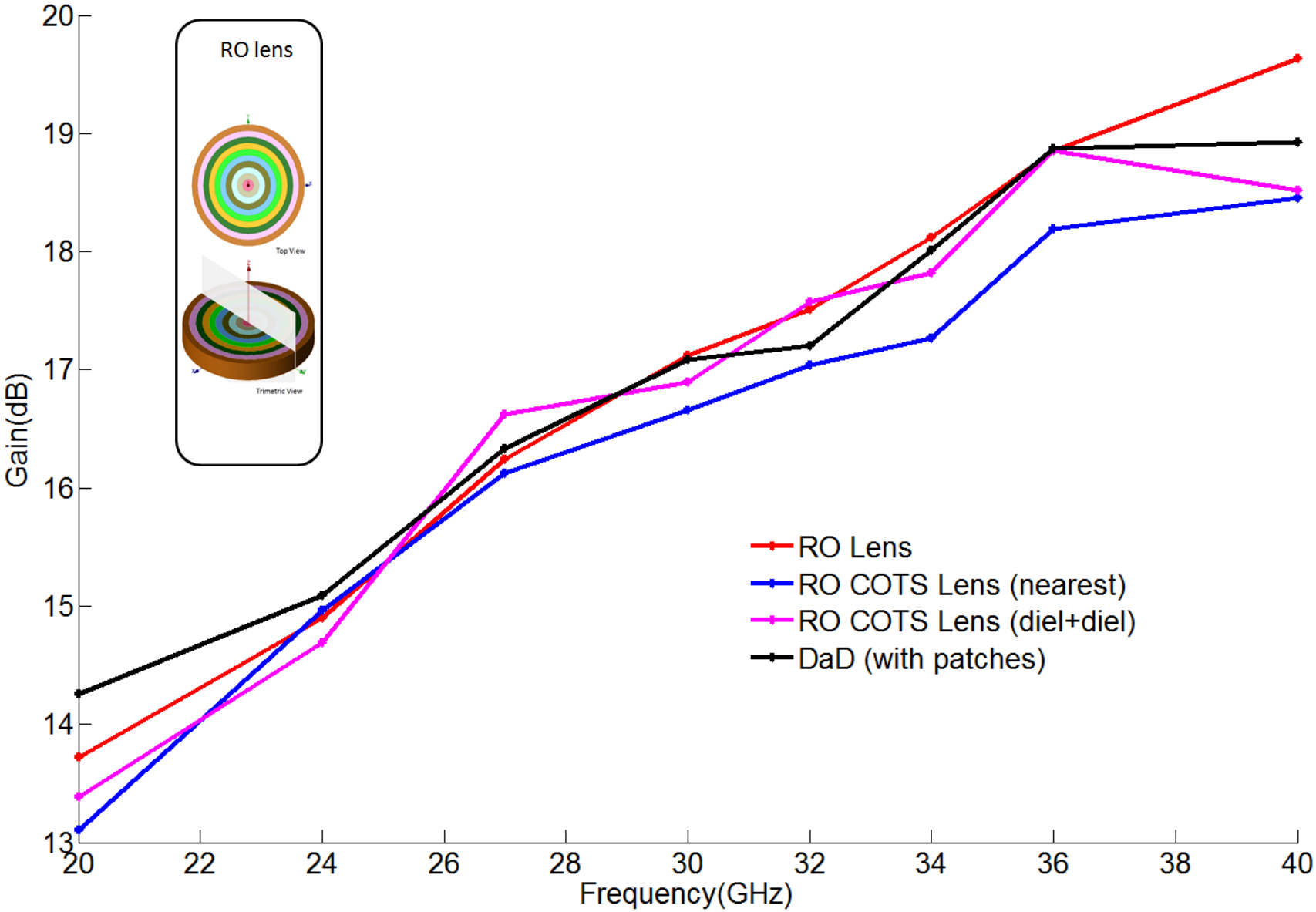




Ring No.	RO Lens (direct calculated values)	RO COTS Lens (nearest COTS) (single layer)	RO COTS Lens (diel+ diel) (single/two layered COTS)		DaD (single/two layered COTS with patches)		
	$\varepsilon_{desired}$	ε_r	ε_r	t_1/t_2 (mm)	ε_r	a (mm)	t_1/t_2 (mm)
1	11.15	10.2	10.2	–	10.2	1.25	–
2	10.64	10.2	10.2	–	10.2	0.98	–
3	9.8	9.8	9.8	–	9.8	--	–
4	8.7	9.2	ε_1=9.2 ε_2=6.15	t_1=8 t_2=1	ε_1=9.2 ε_2=6.15	--	t_1=8 t_2=1
5	7.45	6.15	ε_1=9.2 ε_2=6.15	t_1=4.3 t_2=4.7	ε_1=9.2 ε_2=6.15	--	t_1=4.3 t_2=4.7
6	6.15	6.15	ε_1=9.2 ε_2=6.15	t_1=0.1 t_2=8.9	ε_1=9.2 ε_2=6.15	--	t_1=0.1 t_2=8.9
7	4.88	4.7	ε_1=6.0 ε_2=4.7	t_1=1.58 t_2=7.42	ε_1=6.0 ε_2=4.7	--	t_1=1.58 t_2=7.42
8	3.7	3.66	ε_1=4.5 ε_2=3.66	t_1=0.78 t_2=8.22	ε_1=4.5 ε_2=3.66	--	t_1=0.78 t_2=8.22
9	2.64	2.75	ε_1=3.0 ε_2=2.5	t_1=2.75 t_2=6.25	ε_1=3.0 ε_2=2.5	--	t_1=2.75 t_2=6.25
10	1.73	2.17	ε_1=2.17 ε_2=1.0	t_1=6.16 t_2=2.84	ε_1=2.17 ε_2=1.0	--	t_1=6.16 t_2=2.84

Gain

(RO Lens, different configurations)



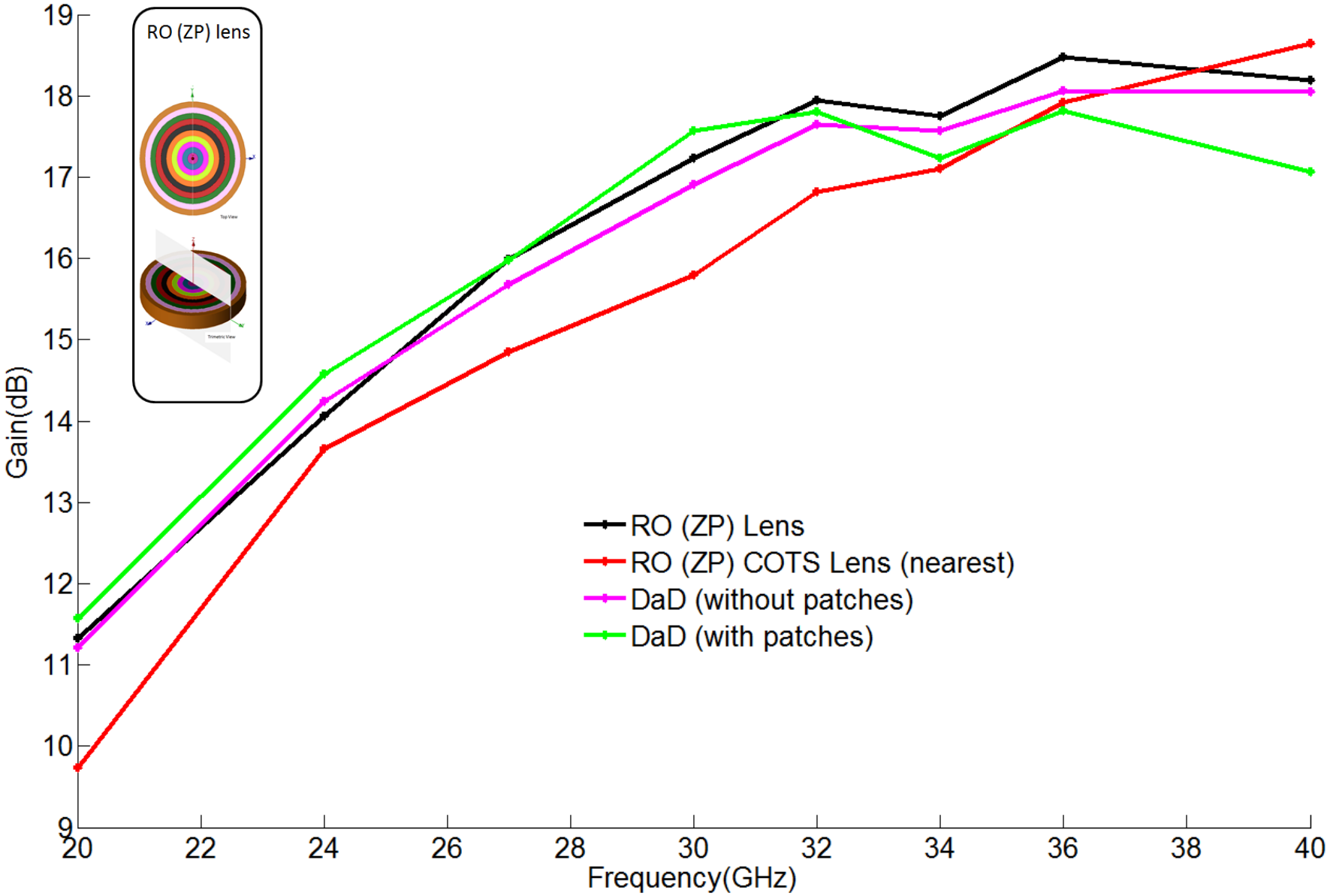
RO (ZP) Lens

(Different configurations)

Ring No.	RO LENS (direct calculated values)	RO (ZP) LENS (Zoned values from RO Lens)	RO (ZP) COTS LENS (nearest COTS)	DaD (with patches) (single/two layered COTS with patches)			DaD (without patches) (No patches, take higher and lower dielectrics than desired)	
	$\varepsilon_{desired}$	$\varepsilon_{desired}$	ε_r	ε_r	Patch ('a', mm)	t_1(mm)	ε_r	t_1/t_2 (mm)
1	11.15	4.96	4.7	4.7	0.98	--	ε_1=6.0 ε_2=4.5	t_1=3.1 t_2=5.9
2	10.64	4.62	4.5	4.5	0.81	--	ε_1=6.0 ε_2=4.5	t_1=1.1 t_2=7.9
3	9.8	4.08	3.66	3.66	1.43	--	ε_1=4.5 ε_2=3.66	t_1=4.7 t_2=4.3
4	8.7	3.38	3.27	3.27	0.95	--	ε_1=3.55 ε_2=3.27	t_1=4.3 t_2=4.7
5	7.45	2.62	2.5	2.5	0.95	--	ε_1=3.0 ε_2=2.5	t_1=2.52 t_2=6.48
6	6.15	1.87	1	ε_2:2.17 ε_1:1.0	0.4	t_1=2.1	ε_1=2.17 ε_2=1.0	t_1=7.01 t_2=1.99
7	4.88	1.20	1	ε_2:2.17 ε_1:1.0	0.76	t_1=0.76	ε_1=2.17 ε_2=1.0	t_1=1.9 t_2=7.1
8	3.7	3.7	3.66	3.66	0.8	--	ε_1=4.5 ε_2=3.66	t_1=0.7 t_2=8.3
9	2.64	2.64	2.5	2.5	1	--	ε_1=3.0 ε_2=2.5	t_1=2.75 t_2=6.25
10	1.73	1.73	1	ε_2:2.17 ε_1:1.0	0.66	t_1=3.1	ε_1=2.17 ε_2=1.0	t_1=6.17 t_2=2.83

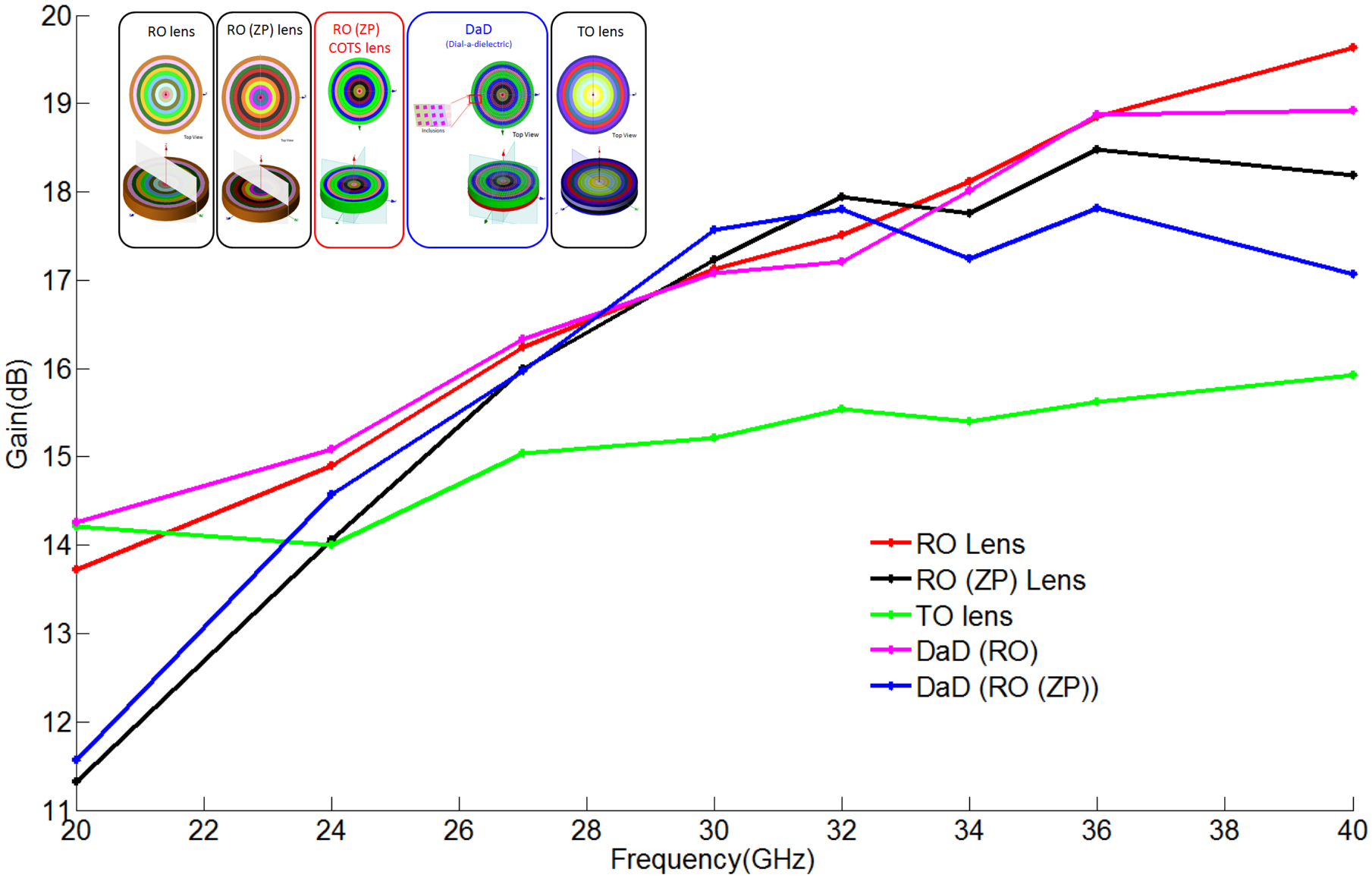
Gain

(RO (ZP) Lens, different configurations)



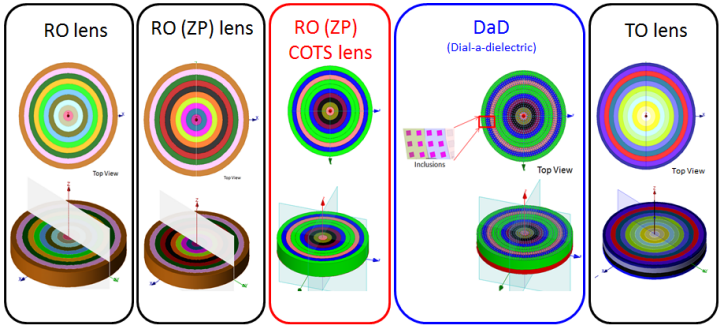
Gain

(Different Lenses)



TO Lens: R. Yang, W. Tang, and Y. Hao, "A broadband zone plate lens from transformation optics," Opt. Express 19, 12348-12355 (2011).

Conclusion



- **Presented New Lens Designs (viz., Dial-a-dielectric). Center frequency is 30GHz; desired operating frequency band ranges from 20 to 40 GHz.**

- **Design strategy:**
  - **Choose the nearest COTS material available for desired ε_r and then tweak it by printing square patch on top of the dielectric rings to realize the desired ε_r.**
  - **If the desired ε_r is less than that of COTS material then use multi-layer dielectrics to realize an ε_r that is close to the desired one. Tweak the effective ε_r realized above, by using printed patches on top, to meet the goal for the desired ε_r .**

- **Gain is comparable to that of RO(ZP) lens in frequency range of 20-38 GHz.**
  - **Between 20-37.5GHz the difference in gain is less than 0.5 dB**
  - **Between 38-40GHz the difference in gain is around 1 dB**

- **Performance of the DaD lens, realized by following the strategy outlined above, is comparable to that of the RO(ZP) lens, which requires materials that are *not available* commercially.**

- **DaD-based design performs better than the TO lens**

References

[1] R. Yang, W. Tang, and Y. Hao, "A broadband zone plate lens from transformation optics," Opt. Express, vol. 19, no. 13, pp. 12348–12355, 2011.

[2] R. Yang, W. Tang, Y. Hao, and I. Youngs, "A coordinate transformation based broadband flat lens via microstrip array," IEEE Antennas and Wireless Propagation Letters, vol. 10, pp. 99–102, 2011.

[3] N. Kundtz and D. R. Smith, "Extreme-angle broadband metamaterial lens," Nat. Mater., vol. 9, no. 123, pp. 129–132, 2009.

[4] Y. Zhang, R. Mittra and W. Hong, "A zoned two-layer flat lens design," International Workshop on Antenna Technology (iWAT), pp. 412–415, 7–9 March, 2011

[5] Y. Zhang, R. Mittra, and W. Hong, "On the synthesis of a flat lens using a wideband low-reflection gradient-index metamaterial," J. of Electromagnetic Waves and Appl., vol. 25, p. 2178–2187, 2011.

[6] Y. Zhang, R. Mittra, and W. Hong, "Systematic design of planar lenses using artificial dielectrics." Antennas and Propagation Society International Symposium (APSURSI), 2010.

[7] S. Jain, M. Abdel-Mageed and R. Mittra, "Flat-Lens Design Using Field Transformation and Its Comparison With Those Based on Transformation Optics and Ray Optics," Antennas and Wireless Propagation Letters, IEEE , vol. 12, pp. 777–780, 2013